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Intelligent Variable Joint Impedance Control and Development of a New Whole-Sensitive Anthropomorphic Robot Arm

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***Abstract*—The paper focuses on design and control of a new anthropomorphic robot arm enabling the torque measurement in each joint to ensure safety while performing tasks of physical interaction with human and environment. When the contact of the arm with an object occurs, local impedance algorithm provides active compliance of corresponding robot arm joint. Thus, the whole structure of the manipulator can safely interact with unstructured environment. A novel variable control strategy was elaborated to increase the robot functionality and to achieve human-like dynamics of interaction. In the paper, we detail the design procedure of 4-DOF robot arm and optical torque sensors. The experimental results of variable joint impedance control show that proposed approach not only provides safe interaction of entire structure of robot arm with a person, but also improves the effectiveness of contact task performance, enables thus to contact with environment in a delicate manner.**

I. INTRODUCTION

NEW technologies and achievements in humanoid robotics will allow to make a new step in robotics in near future – to introduce robot as daily activity assistant [1] in human domain (such as offices, homes, hospitals). In service applications of robotics, human-robot interaction represents a crucial factor for a robot design and imposes strict requirements on its behavior and control in order to ensure safe interaction with environment and effectiveness while target task execution.

Conventional straightforward approaches to controlling the interaction between a manipulator and an environment are based on compliant control of a robot arm according to applied force measured at the tip of the end-effectors. However, collision or expected contact with environment may occur on the entire surface of the robot arm producing interactive forces. In the recent years, several effective methods on enhancement of contact detection ability of manipulator were reported. To avoid collisions in time-varying environment, Lumelsky et al. [2] proposed to cover manipulator with a sensitive skin capable of detecting nearby objects. As this device integrates a huge amount of small sensors incorporated in tiny rigid platform, and requires complicated wiring and signal processing hardware, such devices have high cost and reliability issues. Besides, sensitive skin provides only contact pattern information. Further improvement in human-robot interaction was achieved by using passively compliant joints and whole-body tactile sensors for detecting pressure distribution [3]. Whereas the mechanical leaf springs introduced in each joint allow achieving fast response to external disturbance, they can also cause vibrations and unstable dynamics.

Fig.1. Developed whole-sensitive robot arm.

Another line of research is directed to the development of collision detection system without using external sensors [4]. Such system recognizes collisions based on the difference between the actual torque applied to the joints and the reference torque calculated from manipulator dynamics, and then generates the compliant motion in response to disturbance. However, inaccuracy in dynamic model parameters deteriorates sensitivity threshold up to 17.4 N at the elbow joint. The dexterous robot-human cooperative work requires continuous precise measurement of force in range of 0-50 N.

The traditional teleoperated systems also suffer from the basic safe human-robot interaction issues. A slave robot controlled by an operator mainly performs the manipulations in unknown and unstructured human environment. The

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operator has to move the slave robot arm to the target position, and to avoid obstacles simultaneously. However, operators cannot accomplish both tasks in real time, and they are not perfect in planning of collision-free motion in dynamic unstructured surroundings. Recent researches on teleoperation focus on automation of collision avoidance and contact task based on information from sensors, allowing thus operator to concentrate on the task to be performed. The Robonaut teleoperated robot was developed to assist in-space operations and work with humans in space exploration [5]. In the developed system, operator moves the robot arm until the palm equipped with force sensors contacts the object. The rest parts (elbow, forearm, and upper arm) of the manipulator pose the hazard for humans and structure itself.

Our main research is devoted to realization of teleoperated manipulator and autonomous robot enabling safe interaction with humans. The line of master-slave robot systems (TELESAR I and TELESAR II) was successfully developed in our laboratory [6]. The performance and stability of teleoperation were gradually improved. The slave robot enables to perform dexterous operations by means of 7-DOF arms and 8-DOF hands. The safety in interaction at the tip of the end-effector is provided by impedance control algorithm. The external force is measured by the 6-axis torque/force sensor.

To realize safe physical contact of entire robot arm structure with human and guarantee collision avoidance, our primary idea is concentrated on the design of whole-sensitive robot arm (by using distributed torque sensors in each joint). When contact with environment occurs, manipulator automatically adjusts its dynamic parameters (stiffness and damping) accordingly to the measured external force. The newly developed anthropomorphic manipulator having 4-DOF arm and 8-DOF hand (Fig. 1) is capable to safely interact with environment wherever contact occurs on the arm surface.

The first part of the paper is addressed to the description of the development of whole-sensitive robot arm and new optical torque sensors. In the second part, we discuss the elaborated intelligent variable impedance control algorithm, and experimental results.

II. Design of the New Anthropomorphic Robot Arm

From the safety point of view, to minimize injures in case of collision, most of the robot parts were manufactured from aluminium alloys to obtain as much lightweight structure as possible. The robot links were designed in round shape to reduce impact force. The distribution of the arm joints replicates the human arm structure in order to make it easy to operate using kinesthetic sensation during teleoperation.

To remove mechanical subsystems without disassembling the main structure when the failures do occur, we have been using a modular approach while designing anthropomorphic robot arm. Therefore, we selected CSF-series gear head type of Harmonic Drive instead of compact and lightweight component one. The Harmonic Drive offers such advantages as accurate positioning, high torque capability, torsional stiffness, and high single stage ratios. Developed teleoperated robot arm has 4-DOF: Roll, Pitch, Yaw joints of the shoulder, and Pitch joint of elbow. Each joint is equipped with optical torque sensor directly connected to the output shaft of Harmonic Drive. The sizes and appearance of the arm were chosen so that the sense of incongruity during interaction with human is avoided. We kept the arm proportions the same as in average height human: upper arm length L_1 - 0.308 m; upper arm circumference - 0.251 m (diameter 0.080 m); forearm length L_2 - 0.241 m; forearm circumference - 0.189 m (diameter 0.06 m). The 3D CAD model of the developed arm and coordinate systems based on Denavit-Hartenberg convention are represented in Fig. 2.

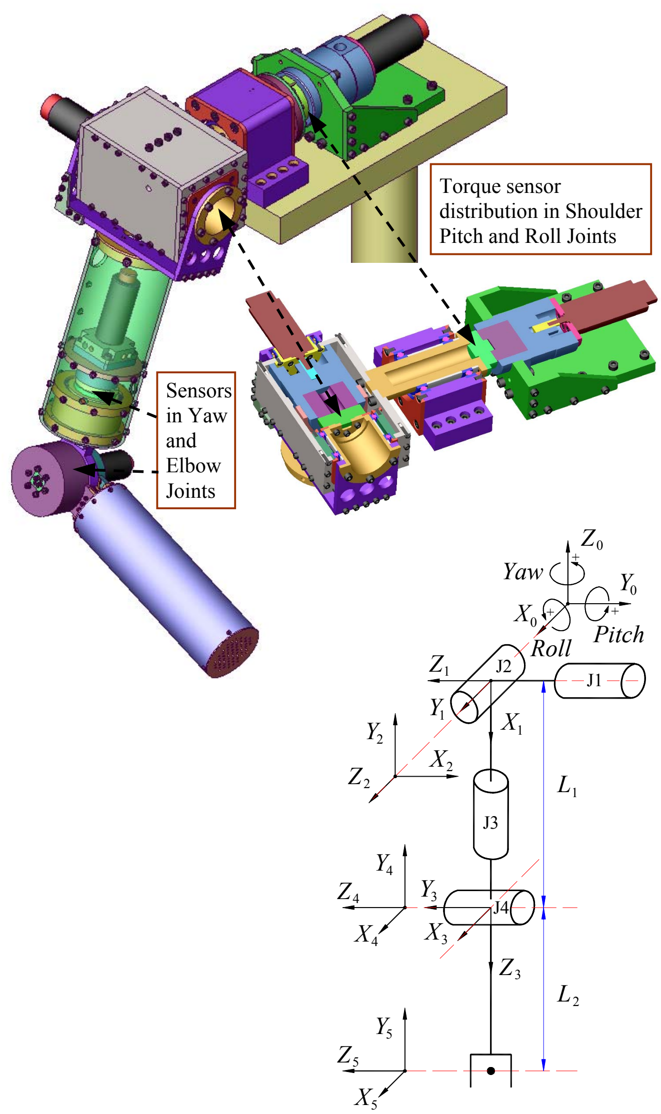

Fig. 2. 3D CAD arm model and coordinate systems.

The principal specifications of the developed arm are given in Table I.

TABLE I
PRINCIPAL SPECIFICATIONS

Parameters	Arm joints			
	Shoulder			Elbow
	J1, Pitch	J2, Roll	J3, Yaw	J4, Pitch
Mobility range (New robot arm/ Human arm) [deg]	-180 to 180 (-60 to 180)	-180 to10 (-165 to 0)	-180 to 180 (-60 to 180)	0 to 112 (0 to 130)
Motor power [W], motor type	90, Maxon RE 35	60, Maxon RE 35	26.6, Faulhaber 2657	26.6, Faulhaber 2657
Harmonic drive rated torque [Nm], (type/ gear ratio)	7.8, (CSF-14-G H /100)	7.8, (CSF-14-G H /100)	5.0, (CSF-11-2 XH/100)	5.0, (CSF-11-2 XH/100)

III. Development of the New Optical Torque Sensor

To facilitate torque-controlled joints of the robots, the authors in [7]-[9] devised magnetostrictive, eddy-current and strain-gauge-based torque sensors. In our previous work, we described in detail the crucial shortcomings of such techniques of the torque measurement, and pointed out the motivations behind using an optical approach [10]. We developed new optical torque sensors having high reliability, high accuracy (even in electrically noisy environment), easy mounting procedure, and low price. The novelty of our method is application of the ultra-small size photointerrupter (PI) RPI-121 as sensitive element to measure relative motion of sensor components. The dimensions of the PI (RPI-121: 3.6 mm × 2.6 mm × 3.3 mm) and its weight of 0.05 g allow realization of compact design. Furthermore, PI also has small influence from the electromagnetic field and stray light, good linearity and high accuracy.

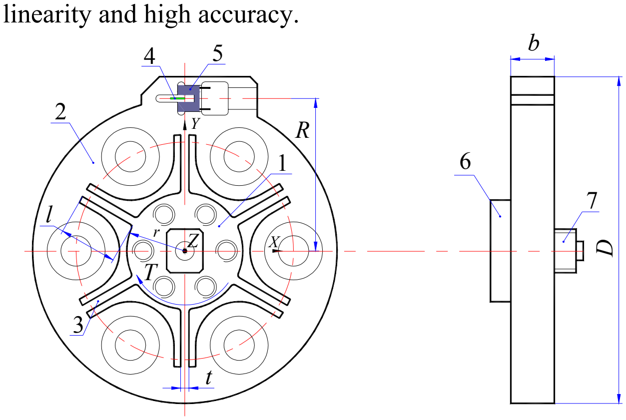

Fig. 3. Hub-spoke structure layout.

The detector (Fig. 3) consists of inner part 1 connected by flexure 3 with outer part 2, shield plate 4, fixed PI 5, and protrusions 6, 7. The sensors were manufactured from one piece of high yield-strength AISI 4135 steel using wire electrical discharge machining (EDM) cutting. To protect the sensor against influence of bending moment, the simple supported loaded shaft configuration was implemented.

IV. Joint Impedance Control

A. Joint Impedance Control

The dynamic equation of an n DOF manipulator in joint space coordinates (during interaction with environment) is given by:

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + \tau_f(\dot{\theta}) + g(\theta) = \tau + \tau_{EXT}, \quad (1)$$

where $\theta, \dot{\theta}, \ddot{\theta}$ are the joint angle, the joint angular velocity, and the joint angle acceleration, respectively; $M(\theta) \in R^{n\times n}$ is the symmetric positive definite inertia matrix; $C(\theta, \dot{\theta}) \in R^n$ is the vector of Coriolis and centrifugal torques; $\tau_f(\dot{\theta}) \in R^n$ is the vector of actuator joint friction forces; $g(\theta) \in R^n$ is the vector of gravitational torques; $\tau \in R^n$ is the vector of actuator joint torques; $\tau_{EXT} \in R^n$ is the vector of external disturbance joint torques.

People can perform dexterous contact tasks in daily activities while regulating own dynamics according to time-varying environment. To achieve skillful human-like behavior, the robot has to be able to change its dynamic characteristics depending on time-varying interaction forces. The most efficient method of controlling the interaction between a manipulator and an environment is impedance control. This approach enables to regulate response properties of the robot to external forces through modifying the mechanical impedance parameters. The graphical representation of joint impedance control is given in Fig. 4.

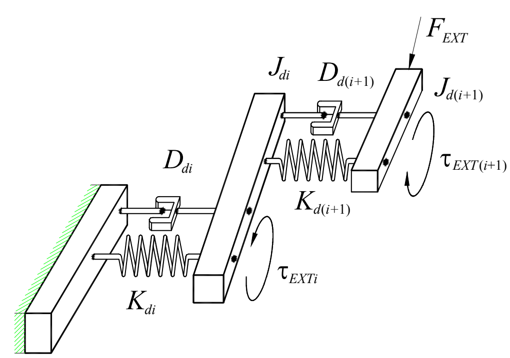

Fig. 4. Concept of the local impedance control.

The desired impedance properties of *i-th* joint of manipulator can be expressed as:

$$J_{di}\Delta\ddot{\theta}_i + D_{di}\Delta\dot{\theta}_i + K_{di}\Delta\theta_i = \tau_{EXTi};\ \Delta\theta_i = \theta_{ci} - \theta_{di}, \quad (2)$$

where J_{di}, D_{di}, K_{di} are the desired inertia, damping, and stiffness of *i-th* joint, respectively; τ_{EXTi} is torque applied to *i-th* joint and caused by external and gravity forces, $\Delta\theta_i$ is the difference between the current compliant angle θ_{ci} and desired one θ_{di}. The state-space presentation of the equation of local impedance control is written as follows:

$$\begin{bmatrix} \Delta\dot{\theta}_i \\ \dot{v}_i \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -K_d/J_d & -D_d/J_d \end{bmatrix} \begin{bmatrix} \theta_i \\ v_i \end{bmatrix} + \begin{bmatrix} 0 \\ 1/J_d \end{bmatrix} \tau_{EXTi}(t), \quad (3)$$

or:

$$\begin{bmatrix} \Delta\dot{\theta}_i \\ \dot{v}_i \end{bmatrix} = A \begin{bmatrix} \theta_i \\ v_i \end{bmatrix} + B\tau_{EXTi}(t), \quad (4)$$

where the state variable is defined as $v_i = \Delta\dot{\theta}_i$; A, B - matrices. After integration of (4), the discrete time presentation of the impedance equation is expressed as:

$$\begin{bmatrix} \Delta\theta_{k+1} \\ \Delta\dot{\theta}_{k+1} \end{bmatrix} = A_d \begin{bmatrix} \Delta\theta_k \\ \Delta\dot{\theta}_k \end{bmatrix} + B_d T_{EXT(k)}. \quad (5)$$

To achieve the fastest possible non-oscillatory response on the external force, we assigned the eigenvalues λ_1 and λ_2 of matrix A as real and equal $\lambda_1=\lambda_2=\lambda$, $\lambda>0$. By using Cayley-Hamilton method for matrix exponential determination, we have:

$$A_d = e^{\lambda T} \begin{bmatrix} 1-\lambda_1 T & T \\ -D_d T/(4J_d) & 1-\lambda_1 T - D_d T/J_d \end{bmatrix}, \quad (6)$$

$$B_d = \left(A_d - I\right) A^{-1} B = -\frac{1}{K_d} \begin{bmatrix} e^{\lambda T}(1-\lambda T)-1 \\ -\left(D_d/(2J_d)\right)^2 T e^{\lambda T} \end{bmatrix}, \quad (7)$$

where T is the sampling time; I is the identity matrix.

There are several conflicting requirements on the choice of dynamics parameters of impedance model to provide effectiveness and functionality of robot in tasks of physical interactions fulfilled in co-operation with humans, and to ensure the collision avoidance. For example, while accomplishing service tasks for human in the autonomous mode, it is required to provide high stiffness (to ensure small position error during object handling) and high damping (for good velocity tracking). In the case of collision, the low stiffness is necessary to reduce the impact forces. Realization of human following motion – one of the most important human-robot cooperation functions – also imposes specific requirements on desired impedance parameter selection. Basically, there are two types of solution of this problem: adaptive and functional adjustments of impedance parameters. In the adaptive control, damping and stiffness of the system are gradually adjusted according to sensed dynamics and contact forces [11]. However, due to parametric uncertainties of the robot dynamics model, it is difficult to obtain the complete description of the dynamics. Therefore, model-based adaptive impedance control must rely on either repeated motions or time for adaptation to achieve convergence to the desired system parameters.

In the functional approaches, current impedance parameters have predetermined relations to the current sensed variables. Generally, these methods presume determining the current stiffness and damping matrices functionally dependent on sensed variables. The main idea of the paper [12] is that involving contact between slave robot and the environment can be classified according to the angle between commanded velocity and the contact force. It is supposed that force and velocity vectors are usually parallel when the impact occurs or when the object is being pushed. So, the functional dependency of stiffness and damping on angle between sensed force and velocity vectors was proposed. In real co-operation tasks and, especially, collisions, these vectors can be not only parallel, but also have independent arbitrary directions according to external force coming direction. Another line of variable impedance research is directed to estimation of human arm stiffness [13]. The proposed variable impedance controller varies a damping parameter of target impedance in proportion to an estimated value of the human arm stiffness. Despite the fact that robot can effectively follow the human arm motion, it cannot perform task autonomously. Besides, only robot end-effector impedance parameters can be adjusted. We elaborated a new methodology for impedance parameter adjustment based on the interaction mode, and providing dynamic stability of the system.

B. Intelligent Variable Joint Impedance Control

The research on impedance characteristics of human arm shows that, while pushing or pulling the object naturally, human arm stiffness and damping behavior can be approximated by exponential curves [14]. The first essential peculiarity of our control method is that we introduce the exponential functional dependency between sensed force and stiffness to impart the human-like damping and stiffness behavior to the robot arm interacting with environment. The second main feature occurred from the fundamental conflict in impedance selection with regard to current working conditions. We consider the threshold external disturbance torque value τ_{EXTth} to distinct the service task (with high stiffness and damping of joints) from collision avoidance and human following motion tasks requiring low stiffness. This value can be chosen depending on the force necessary to accomplish service task. We assigned the specific magnitude of τ_{EXTth} to each joint of robot arm.

The procedure of impedance parameters selection (in the example of elbow joint) is as follows. On the first stage, the parameters of desirable impedance model of robot are computed for the case of service task accomplishment and average-level-contact-force of human-robot interaction. The desired stiffness K_{d1} (for static equilibrium case) is calculated from (8) based on the maximum deflection value of joint angle $\Delta\theta_{max}$ caused by external torque τ_{EXT} while service task performance.

$$K_{d1} = \frac{\tau_{EXT}}{\Delta\theta_{\max}} \quad (8)$$

It was defined that external torque of 1 Nm results in $\Delta\theta_{i\max}$ of 0.1 rad giving the K_{d1} of 10 (Nm/rad). The desired damping is expressed as:

$$D_{d1} = 2\zeta\sqrt{K_{d1}J_{d1}} \quad (9)$$

To achieve fast response without oscillations on the external torque we defined damping coefficient ζ of 1.05. The value of desired inertia J_{d1} of 0.1 (kg·m^2) was assigned to realize fast response tracking. Thus, the value D_{d1} of 2.1 (Nm·s/rad) was derived from (9). These parameters are valid till the interaction force does not cause the overload of robot arm. When sensed value of the torque is larger then threshold level, robot recognizes this condition as collision or human following motion mode, and adjusts its dynamics parameters (stiffness and damping) in the same way as humans in order to provide smooth natural interaction. To realize such continuous change of dynamics, we are using exponential relation between external disturbance torque and desired stiffness:

$$K_{d2} = K_{d1}e^{\mu(\tau_{EXT}-\tau_{EXTth})}, \quad (10)$$

where K_{d2} is the variable desired stiffness aimed at soft compliant interaction; μ is the coefficient defining the level of decreasing of arm joint stiffness in response on increasing external torque value.

The desired damping is adjusted to prevent force responses from being too sluggish while changing stiffness values, and to ensure contact stability:

$$D_{d2} = 2.1\sqrt{K_{d2}J_{d1}} = 2.1e^{0.5\mu(\tau_{EXT}-\tau_{EXTth})}\sqrt{K_{d1}J_{d1}} \quad (11)$$

Then, variable joint impedance controller is described by:

$$J_{di}\Delta\ddot{\theta}_i + 2.1e^{0.5\mu(\tau_{EXTi}-\tau_{EXTth})}\sqrt{K_{d1}J_{d1}}\Delta\dot{\theta}_i + K_{d1}e^{\mu(\tau_{EXTi}-\tau_{EXTth})}\Delta\theta_i = \\ = \tau_{EXTi};\ \Delta\theta_i = \theta_{ci} - \theta_{di} \quad (12)$$

To verify the theory and to evaluate the feasibility and performance of the proposed impedance controller, the experiment with new whole sensitive robot arm was conducted. To ensure the effectiveness of service task accomplishment we decided to implement position-based impedance control (Fig. 5). In this algorithm, compliant trajectory generated by the impedance controller is tracked by the PD control loop. During the experiment, the interaction with arm was performed to exceed join torque threshold level (τ_{EXTth} of 0.6 Nm was assigned, μ = -1.155). The experimental results for the elbow joint – applied torque, stiffness and damping plot, impedance trajectory with constant and variable coefficients, and measured joint angle – are presented in Fig. 6, Fig. 7, Fig. 8, and Fig. 9, correspondingly.

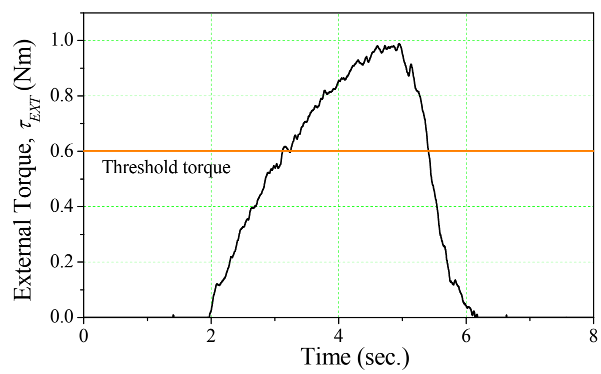

Fig. 6. External torque.

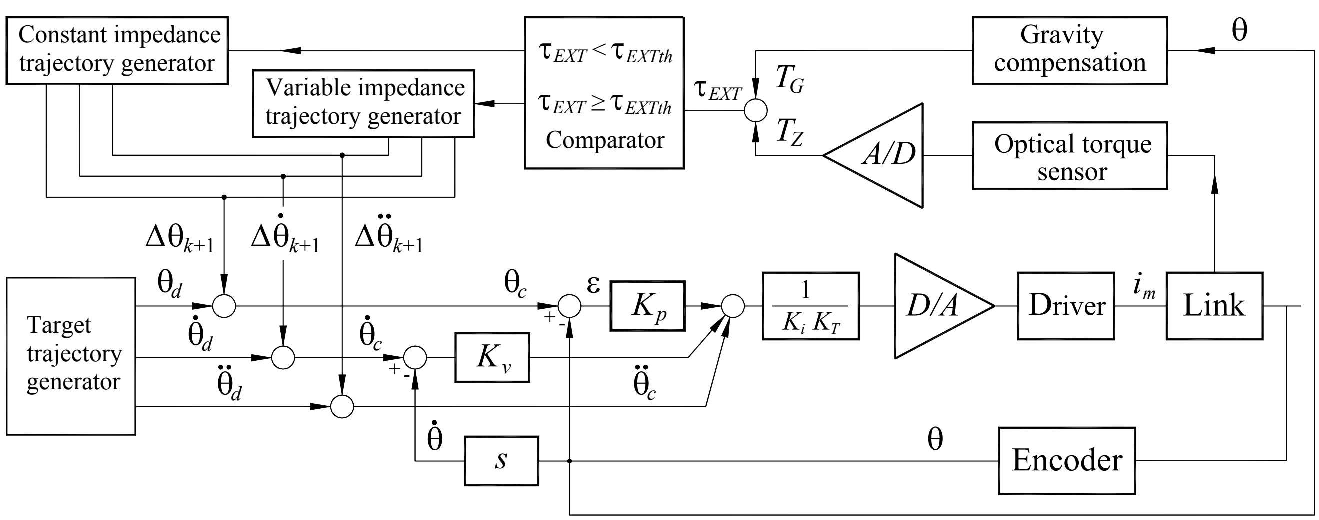

Fig. 5. Block diagram of the position-based impedance control.

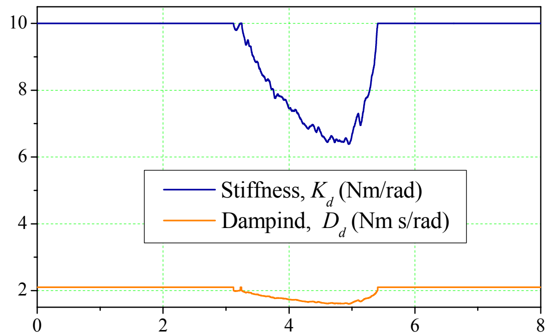

Fig. 7. Variable stiffness and damping parameters.

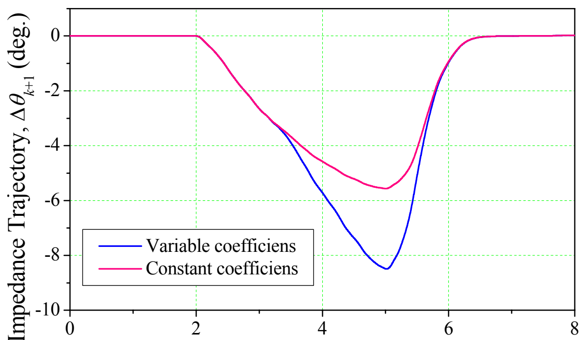

Fig. 8. Measured joint angle.

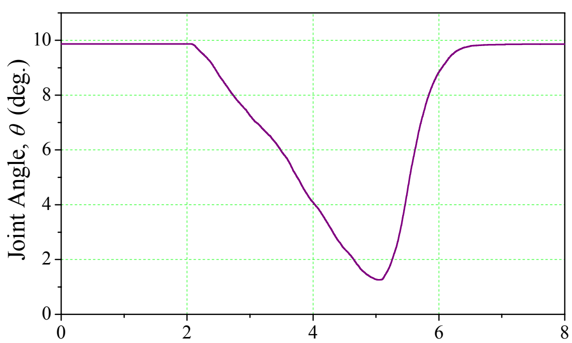

Fig. 9. Trajectories generated by impedance model with constant and variable coefficients.

The experimental results show the successful realization of the variable joint impedance control. While contacting with human, the robot arm generates compliant soft motion according to the sensed force. The plot represented in Fig. 8 shows that the variable impedance control provides better trajectory to avoid impact and to accomplish human following motion than the impedance control with constant coefficients. As we assigned critically damped response of impedance model to disturbance force, output angle ($\Delta\theta_{k+1}$) has ascending-descending exponential trajectory. The conventionally impedance-controlled robot can provide contacting task only at the tip of the end-effector with predetermined dynamics. By contrast, our approach provides delicate continuous safe interaction of all surface of the arm with environment. As the result of the experiments with variable impedance-controlled arm, tactile sensation of soft friendly interaction was really achieved.

V. Conclusion and Future Work

New whole-sensitive teleoperated robot arm was developed to provide human-like capabilities of contact task performing in a broad variety of environments. To facilitate this arm with joint torque measuring ability, the new optical torque sensors having good accuracy, high signal-to-noise ratio and compact sizes were designed and manufactured. The effectiveness of the position-based variable impedance control for providing safe human-robot interaction was experimentally illustrated on a new whole-sensitive robot arm. Our future research will be devoted to elaboration of the approach to precise estimation of external force vector and contact area recognition.

References

[1] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M. Hirata, K. Akachi, and T. Isozumu. "Humanoid Robot HRP 2," in *Proc. 2004 IEEE Int. Conf. Robotics and Automation*, New Orleans, 2004, pp. 1083-1090.

[2] V. J. Lumelsky and E. Cheung, "Real-time collision avoidance in teleoperated whole-sensitive robot arm manipulators," *IEEE Trans. Systems, Man, and Cybernetics,* vol. 23, no. 1, pp.194-203, 1993.

[3] H. Iwata, S. Kobashi, T. Aono, and S. Sugano, "Design of anthropomorphic 4-DOF tactile interaction manipulator with passive joints," in *Proc. 2005 IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Edmonton, Alberta, Canada, 2005, pp. 1785-1790.

[4] S. Morinaga and K. Kosuge, "Compliant motion control of manipulator`s redundant DOF based on model-based collision detection system," in *Proc. 2004 IEEE Int. Conf. on Robotics and Automation*, New Orleans, 2004, pp. 5212-5217.

[5] M.A. Diftler, C. J. Culbert, R. O. Ambrose, Jr. R. Platt, and W. J. Bluethmann, "Evolution of the NASA/DARPA Robonaut control system," in *Proc. 2003 IEEE Int. Conf. Robotics and Automation*, Taipei, 2003, pp. 2543-2548.

[6] R. Tadakuma, Y. Asahara, H. Kajimoto, N. Kawakami, and S. Tachi, "Development of anthropomorphic multi-D.O.F. master-slave arm for mutual telexistence," *IEEE Trans. Visualization and Computer Graphics*, vol. 11, no. 6, pp. 626-636, November 2005.

[7] T. Sakaki and T. Iwakane, "Impedance control of a manipulator using torque-controlled lightweight actuators," *IEEE Trans. Industry Applications*, vol. 28, no. 6, pp. 1399-1405, November 1992.

[8] D. Vischer and O. Khatib, "Design and development of high-performance torque controlled joints," *IEEE Trans. Robotic and Automation*, vol. 11, no. 4, pp. 537-544, August 1995.

[9] G. Hirzinger, A. Albu-Schaffer, M. Hahnle, I. Schaefer, and N. Sporer, "On a new generation of torque controlled light-weight robots," in *Proc. 2001 IEEE Int. Conf. Robotics and Automation*, Seoul, Korea, 2001, pp. 3356-3363.

[10] D. Tsetserukou, R. Tadakuma, H. Kajimoto, and S. Tachi, "Optical torque sensors for implementation of local impedance control of the arm of humanoid robot," in *Proc. 2006 IEEE Int. Conf. Robotics and Automation*, Orlando, 2004, pp. 1674-1679.

[11] R. Carelli and R. Kelly, "Adaptive impedance/force controller for robot manipulators," *IEEE Trans. Automat. Contr.*, vol. 36, pp. 967-972, Aug. 1991.

[12] R. V. Dubey, T. F. Chang, and S. E. Everett, "Variable damping impedance control of a bilateral telerobotic system," *IEEE Control Systems Mag.*, vol. 17, pp. 37-44, Feb. 1997.

[13] T. Tsumugiwa, R. Yokogawa, and K. Hara, "Variable impedance control based on estimation of human arm stiffness for human-robot cooperative calligraphic task," in *Proc. 2002 IEEE Int. Conf. Robotics and Automation*, Washington, DC, 2002, pp. 644-650.

[14] M. M. Rahman, R. Ikeura, and K. Muzutani, "Investigating the impedance characteristics of human arm for development of robot to cooperate with human operators," in *Proc. 1999 IEEE International Conference Systems, Man and Cybernetics*, Tokyo, Japan, 1999, pp. 676-681.